

FLAVOR VIOLATION IN THE SCALAR SECTOR

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In many extensions of the Standard Model, the alignment in flavor space of the fermion mass matrices and the Yukawa coupling matrices can be broken. The physical scalar boson $h(125)$ could then have flavor changing couplings. In this talk, we summarize constraints on such couplings from rare decay searches, and we investigate current and future detection prospects at the LHC. We emphasize the importance of several yet unexplored final states: (i) anomalous single top + h production in $pp \rightarrow th$, arising from tuh couplings (but not from the more widely studied tch couplings); (ii) $pp \rightarrow t + (H^0 \rightarrow hh)$ through tuh couplings in the context of a Two Higgs Doublet Model (2HDM), perhaps the simplest model with flavor violation in the scalar sector; (iii) $pp \rightarrow H^0 \rightarrow \tau\mu$ in the 2HDM context. For all of these processes, we perform a detailed phenomenological studies. Finally, we comment on the possibility of flavor violation combined with CP violation, which may be interesting if the current CMS hint for $h \rightarrow \tau\mu$ gets corroborated.

1 Introduction

The 125 GeV scalar boson discovered by ATLAS and CMS in 2012, while being the last missing piece of the Standard Model (SM), will hopefully also contribute to its demise by deviating from the expected behavior. One such deviation could be a flavor off-diagonal coupling to fermions,^{1–4} which are forbidden in the SM, but are quite naturally expected in many of its extensions. At the effective field theory level, flavor violating scalar couplings have the generic structure (illustrated here for the charged leptons)

$$\mathcal{L} \supset -\frac{\eta_{ij}}{\Lambda^2} \bar{L}^i \tilde{H} e_R^j (H^\dagger H) \quad \rightarrow \quad -y_{ij} \bar{e}_L^i e_R^j h + \dots \quad (1)$$

Here, Λ is the cutoff scale of the effective theory, L^i are the three left-handed SM lepton doublets, e_R^j are the three right-handed charged lepton singlet, H is the SM scalar doublet, $\tilde{H} \equiv i\sigma^2 H^\dagger$, and h is the physical 125 GeV scalar boson. Flavor violating couplings in the quark sector are completely analogous. Possible ultraviolet completions of the Lagrangian in eq. (1) exist for instance in Randall–Sundrum models^{5–7}, supersymmetric models^{8–11}, models aiming to explain the flavor structure of the Standard Model¹², leptoquark models¹³, and in particular in Two Higgs Doublet Models (2HDMs).^{1;8;14–21}

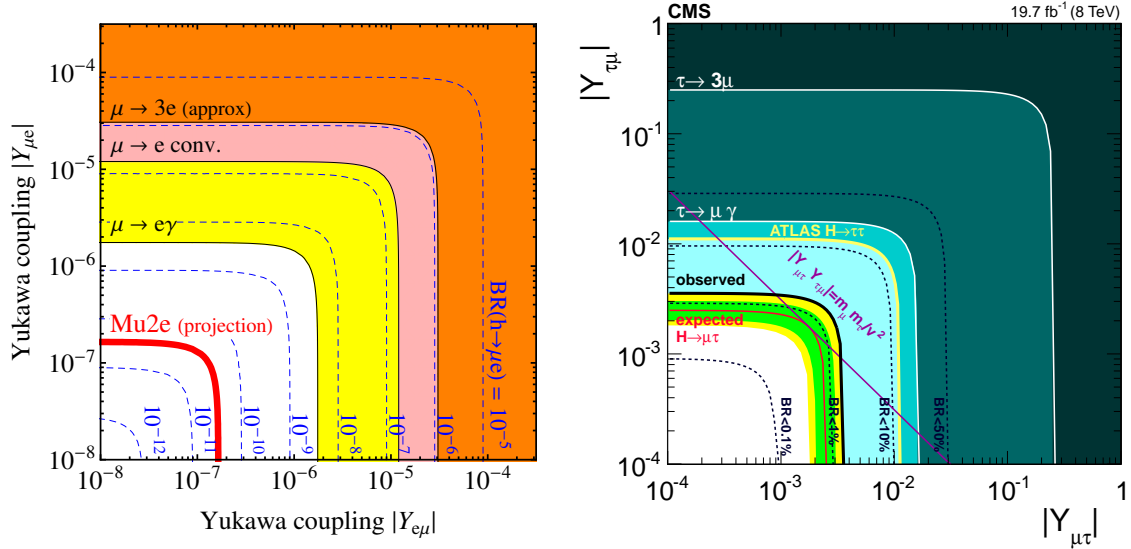


Figure 1 – Constraints on flavor changing couplings of the h boson to leptons, expressed in terms of the Yukawa couplings appearing in eq. (1). In the μ - e sector (left panel⁴), low energy limits are many orders of magnitude stronger than LHC constraints (not shown here), while in the μ - τ sector (right panel²²), the LHC dominates. Note the small (2.3σ) excess in the CMS data on $h \rightarrow \mu\tau$.

Phenomenologically, the operators in eq. (1) can lead to a bonanza of flavor physics observables (rare decays, anomalous electric and magnetic dipole moments, meson oscillations, ...), flavor changing scalar decays like $h \rightarrow \tau\mu$, $h \rightarrow \tau e$, anomalous top quark decays $t \rightarrow hq$, and anomalous single top + h production via $ug \rightarrow th$. In UV completions of eq. (1), many more processes can be important. For instance in the context of 2HDMs, flavor violating couplings of the heavy scalar bosons are expected to be much larger than those of the lightest scalar, so that the reactions $ug \rightarrow tH^0$ and $pp \rightarrow H^0 \rightarrow \tau\mu$ can have sizeable rates. In the following, we discuss the aforementioned processes in more detail.

2 Low Energy Constraints and Current LHC limits on FCNC in the Scalar Sector

Flavor changing neutral current (FCNC) couplings of the h boson to leptons are most strongly constrained by μ - e conversion in nuclei, by flavor changing decays of a heavy lepton to three lighter leptons (e.g. $\tau \rightarrow 3\mu$), and by the radiative decays $\mu \rightarrow e\gamma$, $\tau \rightarrow e\gamma$, and $\tau \rightarrow \mu\gamma$. Currently, radiative decay limits have a slight edge over other constraints, but with future experiments like Mu2e at Fermilab or Mu3e at PSI this will change. We show the current constraints on flavor changing neutral current (FCNC) couplings of the form $h\mu e$ in fig. 1 (a) and on couplings in the μ - τ sector in fig. 1 (b). (Constraints on the e - τ sector are very similar to those on the μ - τ sector⁴.) We see that constraints in the μ - e sector are so tight that the associated LHC process $h \rightarrow \mu e$ is far beyond the experimental reach. On the other hand, $\text{BR}(h \rightarrow \tau\mu)$ or $\text{BR}(h \rightarrow \tau e)$ can be at the per cent level, well within the capabilities of ATLAS and CMS. In fact, CMS has observed a small (2.3σ) excess in $h \rightarrow \tau\mu$ ²². (Note that *either* $\text{BR}(h \rightarrow \tau\mu)$ *or* $\text{BR}(h \rightarrow \tau e)$ can be large, but not both. If both were sizeable, the tightly constrained decay $\mu \rightarrow e\gamma$ would be induced at 1-loop.)

In the quark sector, FCNC processes are tightly constrained by low energy measurements as well. For instance, couplings of the form hqq' (where $q, q' = u, d, s, c, b$) contribute at tree level to neutral meson mixing. The resulting constraints⁴ imply that the only flavor violating h couplings that could be large enough to be observable at the LHC are those involving the top quark, tuh and tch . (Once again, only one of these couplings can be large, but not both, to avoid large contributions to D^0 - \bar{D}^0 meson mixing through box diagrams.) The current experimental

limits on FCNC top- h couplings are

$$\text{BR}(t \rightarrow ch) < 0.0046, \quad \text{BR}(t \rightarrow uh) < 0.0045 \quad (2)$$

from ATLAS²³ and $\text{BR}(t \rightarrow uh) < 0.0047$, $\text{BR}(t \rightarrow ch) < 0.0042$ from CMS²⁴. Both limits are based on combinations of several final states, including in particular multi-lepton and lepton + di-photon signatures.

3 New Probes of FCNC Couplings to Quarks

In the following, we outline several possible routes towards a further improvement of the constraints on tuh and tch couplings.

3.1 $t \rightarrow hq$ and $pp \rightarrow th$

First, we observe that tuh couplings induce not only the widely studied decay $t \rightarrow hu$, but also the process $ug \rightarrow th$ (anomalous single top + h production), which is not included in most searches for FCNC top couplings²⁵. Therefore, the limits on tuh couplings reported by these searches are on the conservative side. For the multi-lepton and lepton + di-photon final states, it was shown²⁵ that inclusion of anomalous single top + h production could lead to an increase in sensitivity by a factor ~ 1.5 . Note that this applies only to tuh couplings, but not to tch couplings. The reason is that the process $cg \rightarrow th$ is suppressed by the small charm quark parton distribution function (PDF) and therefore negligible.

This observation suggests a possible way of distinguishing tuh and tch couplings in case of a discovery. Namely, even though the final states for $pp \rightarrow (t \rightarrow Wb) + (t \rightarrow hq)$ and $ug \rightarrow t + h$ are almost identical, there are differences: in particular, the pseudorapidity (η_h) distribution of the h boson and the sum of lepton charges in multi-lepton final states can be used as discriminants^{25;26}. In $ug \rightarrow th$, the h boson is preferentially emitted in the forward or backward direction, compared to a more central distribution in $pp \rightarrow (t \rightarrow Wb) + (t \rightarrow hq)$, see fig. 2. The reason is that the chiral structure of the tuh coupling implies a chirality flip on the quark line. This is easily possible only if the t quark is emitted opposite to the direction of travel of the initial u quark. The h boson must then travel preferentially in the same direction as the u quark. The forward boost of the h boson is further enhanced by the fact that the center-of-mass frame of the process tends to be boosted in the direction of the (valence) u quark. The discrimination power of the sum of lepton charges can be understood by noting that $ug \rightarrow th$ events are much more frequent than $\bar{u}g \rightarrow \bar{t} + h$ events because of PDF suppression. Quantitatively, one finds that, for a signal that is discovered at the 5σ level, a 2σ discrimination between the tuh and tch hypotheses is possible²⁵. This estimate is for a multi-lepton analysis and takes into account backgrounds, combinatorial uncertainties and detector effects.

Going beyond the traditional multi-lepton and lepton + di-photon searches, a further improvement of the sensitivity to tuh and tch couplings by an $\mathcal{O}(1)$ factor is possible by including so-far unexplored final states²⁵, for instance the fully hadronic processes $pp \rightarrow (t \rightarrow Wb) + (t \rightarrow hq) \rightarrow \text{hadrons}$ and $pp \rightarrow (t \rightarrow Wb) + h \rightarrow \text{hadrons}$. These decays can be successfully reconstructed and exploited using boosted object taggers^{27–31}.

3.2 $pp \rightarrow thh$

In specific models, additional search channels for flavor changing h couplings lend themselves to exploitation. Consider in this context a general (type III) 2HDM in which the components of the second scalar doublet have large FCNC couplings to top quarks, but only a small mixing with the SM-like doublet. Working in a basis in which only one of the two scalar doublets Φ_1 ,

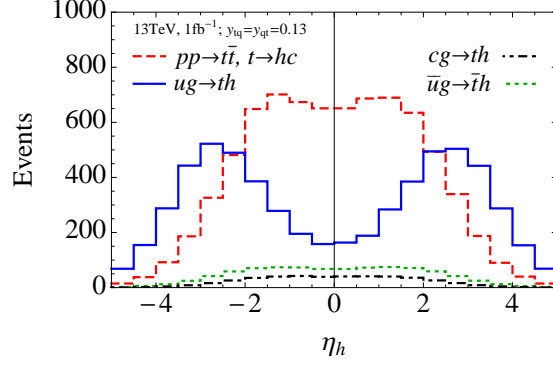


Figure 2 – The parton level pseudorapidity (η_h) distributions of the h boson in $pp \rightarrow (t \rightarrow Wb) + (t \rightarrow hq)$ and in $ug \rightarrow th$.²⁵ Note the preference for forward emission of the h boson in the latter process (see text for details).

Φ_2 has a non-zero vacuum expectation value (vev), we decompose Φ_1 and Φ_2 into

$$\Phi_1 = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + h_1 + iG^0) \end{pmatrix} \quad \Phi_2 = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(h_2 + ih_3) \end{pmatrix}. \quad (3)$$

Here G^\pm and G^0 are the Goldstone bosons that are eaten by the W^\pm and the Z . In the absence of CP violation, h_1 and h_2 mix into the CP even physical scalars h and H^0 , and h_3 is identified with the CP odd scalar A^0 . The scalar potential V of the model depends on three dimensionful parameters and seven dimensionless couplings. The condition that $\Phi_1 = (0, v/\sqrt{2})$, $\Phi_2 = (0, 0)$ should be a minimum of V eliminates two of these parameters, and one further coupling can be dropped here because it is only relevant for scalar self-interactions. The seven remaining parameters can be expressed in terms of the masses m_h , m_{H^0} , m_{A^0} , m_{H^\pm} , the h - H^0 mixing $\sin \alpha$, and two dimensionless parameters λ_3 and λ_7 .³² The Yukawa couplings of the two scalar doublets are given in the up quark sector by

$$\mathcal{L}_{\text{up}} = -\eta_1^{ij} \overline{Q_L^i} \tilde{\Phi}_1 u_R^j - \eta_2^{ij} \overline{Q_L^i} \tilde{\Phi}_2 u_R^j + h.c., \quad (4)$$

with $\tilde{\Phi}_k \equiv i\sigma^2 \Phi_k^\dagger$. The couplings to down quarks and leptons are analogous.

In a 2HDM, flavor changing effects become much more accessible once not only the lightest scalar h , but also its heavier companions can be directly produced. An example is the process $pp \rightarrow tH^0$, mediated by a flavor violating tuH^0 coupling and followed by the decay $H^0 \rightarrow hh$.³² If the (flavor conserving and flavor violating) couplings of H^0 to quarks are not too large, this decay mode can be dominant in large regions of parameter space, as illustrated in fig. 3 (a) for a particular parameter point of the quark flavor violating 2HDM. The most favorable final state to look for $pp \rightarrow t + (H^0 \rightarrow hh)$ consist of one lepton (from top decay), five b quarks, and missing transverse energy. It can be extracted from the background by requiring one isolated, positively charged lepton, at least five jets, and at least four b tags.³² Moreover, p_T and η cuts need to be imposed on these objects, as well as on the reconstructed h bosons. Combinatorial backgrounds can be suppressed by optimizing the invariant masses of two jet pairs and of the fifth jet, the lepton, and the missing energy.

The sensitivity of such a search is illustrated in fig. 3 (b). The parameter point chosen for this plot was selected such that the tuH^0 coupling is the dominant Yukawa coupling of H^0 , i.e. that η_2^{tu} is the only relevant entry of the matrix η_2 from eq. (4). (Note that the complementary coupling η_2^{ut} cannot be too large because of constraints from B meson mixing.³²) We see that the proposed search for $pp \rightarrow t + (H^0 \rightarrow hh)$ is very promising and can easily supersede current and future limits from other search channels.

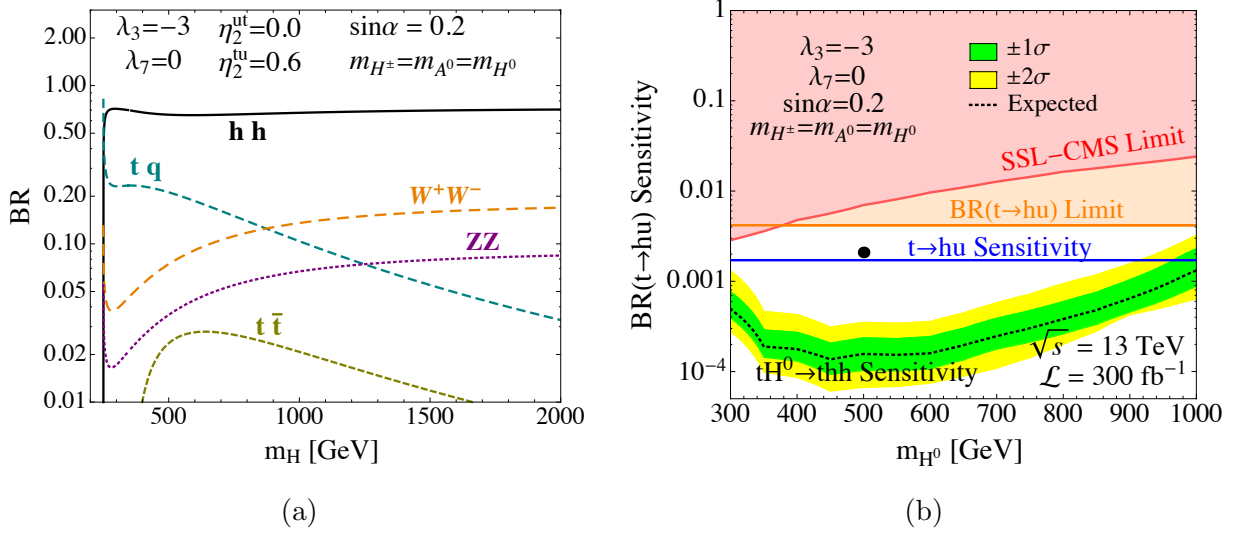


Figure 3 – (a) Branching ratios of the H^0 boson for one parameter point in a quark flavor violating 2HDM.³² (b) Sensitivity to flavor changing couplings of the top quark to the h and H^0 bosons at the same parameter point, expressed here in terms of the branching ratio for $t \rightarrow hq$. The orange and blue lines show the current and conservative future sensitivities, respectively, to $t \rightarrow hu$ using multi-lepton and lepton + di-photon final states²⁵. The red shaded region is the limit from a CMS search for same-sign di-leptons + b jets³³. The Brazilian band shows the predicted sensitivity for the search discussed in the text.³²

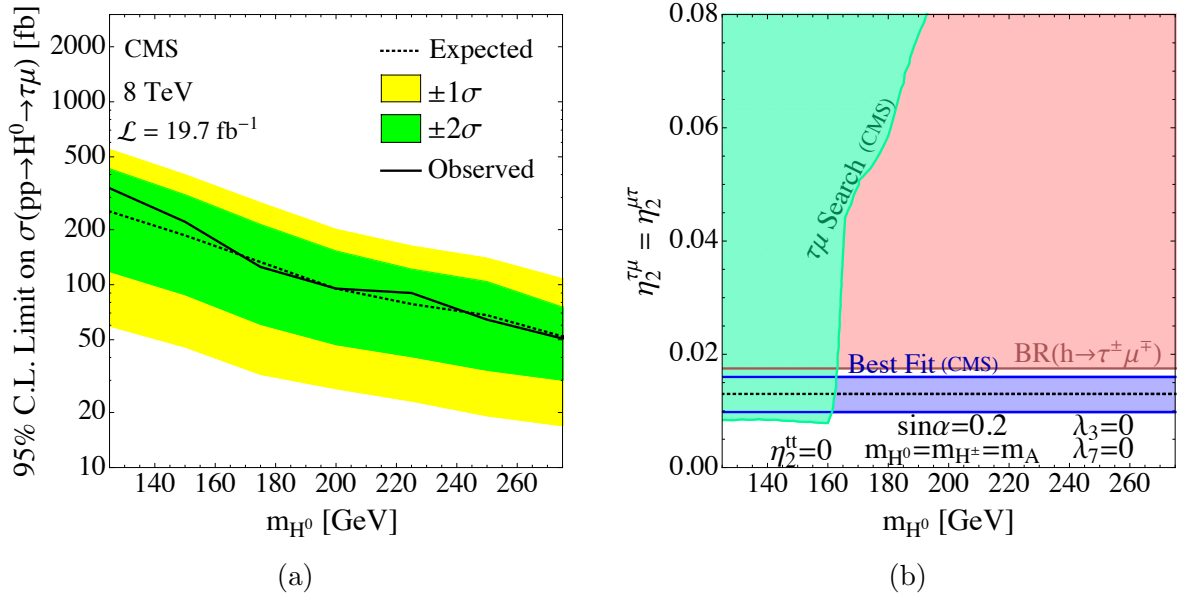


Figure 4 – (a) Constraints on the FCNC decay $H^0 \rightarrow \tau\mu$ of the heavy CP even scalar H^0 in a 2HDM, derived by recasting the CMS search for $h \rightarrow \tau\mu$ ^{22;32}. (b) Resulting constraints on the FCNC Yukawa coupling $\eta_{\tau\mu}$ and $\eta_{\mu\tau}$ of the second scalar doublet (green) compared to the limit from the direct search $h \rightarrow \tau\mu$ (red)²² and the region favored by the small excess in that search (blue 1σ band).

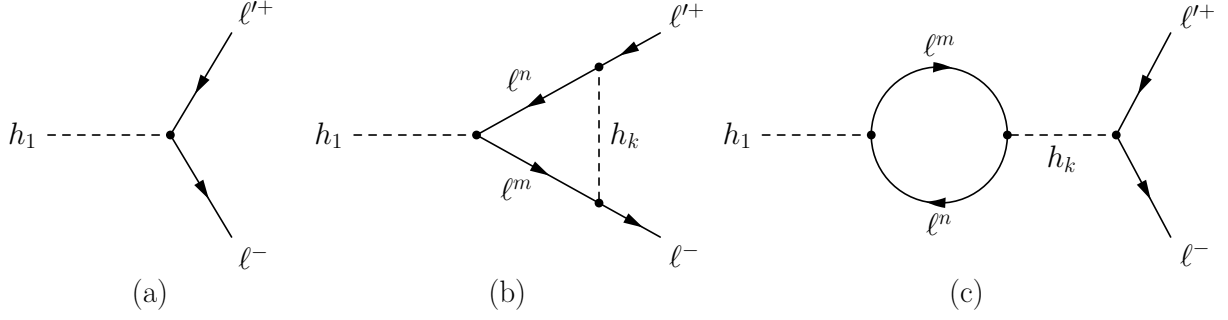


Figure 5 – The tree level and 1-loop diagrams in a 2HDM whose interference can lead to a CP violating asymmetry between $h \rightarrow \tau^+\mu^-$ and $h \rightarrow \tau^-\mu^+$ final states. In these diagrams, h_k ($k = 1, 2, 3$) are the three neutral scalars and ℓ, ℓ', ℓ^m are charged leptons.

4 New Probes of FCNC Couplings to Leptons

Let us now turn to flavor violating couplings of the scalar sector to leptons. Also in this case, the sensitivity in specific model frameworks can be much larger than for the simple EFT from eq. (1). We consider again a type III 2HDM and investigate to what extent current searches for μ - τ resonances²² constrain the FCNC decay $H^0 \rightarrow \tau\mu$. As for FCNC in the quark sector, this decay is expected to have a much large branching ratio than $h \rightarrow \tau\mu$, which offsets the smaller production cross section of H^0 . Recasting the CMS search for $h \rightarrow \tau\mu$ ^{22,32}, we find the limits shown in fig. 4. Note that above $m_{H^0} = 2m_W$, the dominant H^0 decay mode becomes $H^0 \rightarrow W^+W^-$, reducing the branching ratio to the $\tau\mu$ final state and thus limiting the parameter sensitivity in this mass range, see fig. 4 (b).

5 CP Violation in FCNC h Decays

If flavor violation in the scalar sector is discovered—for instance if the CMS hint for $h \rightarrow \tau\mu$ ²² should be corroborated with 13 TeV data—it stands to reason to ask whether it could be accompanied by CP violation. In fact, the resulting signature—an asymmetry between $h \rightarrow \tau^+\mu^-$ and $h \rightarrow \tau^-\mu^+$ would offer a very direct probe of CP violation. Figure 5 illustrates how such an asymmetry could arise in a type III 2HDM from the interference between tree level and 1-loop processes. A detailed phenomenological analysis³⁴ shows that, like all searches for CP violation in the scalar sector, also the search for CP violation in $h \rightarrow \tau\mu$ requires very large integrated luminosity before one can hope to observe a signal. The reason is that a loop-suppressed effect must be observed on top of an already small branching ratio. Assuming an $h \rightarrow \tau\mu$ signal at the level hinted at by CMS²², a detection of a CP asymmetry may be possible at the high-luminosity LHC if the mixing angle between the SM-like h boson and its heavy partners is small and if the heavy scalars are close to each other in mass.³⁴

6 Summary

In summary, we have reviewed from a phenomenologist’s point of view the current status of FCNC searches in the scalar sector. We have outlined a number of possible directions for future experimental work, including in particular (i) searching explicitly for the so-far neglected process $pp \rightarrow th$, which could be exploited to distinguish tuh and tch couplings in the event of a discovery; (ii) exploiting new final states, for instance in the fully hadronic processes $pp \rightarrow (t \rightarrow Wb) + (t \rightarrow hq) \rightarrow \text{hadrons}$ and $pp \rightarrow th \rightarrow \text{hadrons}$; (iii) searching for FCNC decays of heavy scalar bosons, which can have very large branching ratios in 2HDMs; (iv) Searching for CP violation in $h \rightarrow \tau\mu$.

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References

- [1] J. D. Bjorken and S. Weinberg, *Phys. Rev. Lett.* **38**, 622, (1977).
- [2] B. McWilliams and L.-F. Li, *Nucl. Phys.* **B179**, 62, (1981).
- [3] G. Blankenburg, J. Ellis, and G. Isidori, *Phys.Lett.* **B712**, 386–390, (2012), [arXiv:1202.5704](#).
- [4] R. Harnik, J. Kopp, and J. Zupan, *JHEP* **1303**, 026, (2013), [arXiv:1209.1397](#).
- [5] M. Blanke et al., *JHEP* **03**, 001, (2009), [arXiv:0809.1073](#).
- [6] S. Casagrande et al., *JHEP* **10**, 094, (2008), [arXiv:0807.4937](#).
- [7] A. Azatov, M. Toharia, and L. Zhu, *Phys. Rev.* **D80**, 035016, (2009), [arXiv:0906.1990](#).
- [8] J. L. Diaz-Cruz and J. Toscano, *Phys.Rev.* **D62**, 116005, (2000), [hep-ph/9910233](#).
- [9] L. de Lima et al., *JHEP* **11**, 074, (2015), [arXiv:1501.06923](#).
- [10] A. Arhrib, Y. Cheng, and O. C. W. Kong, *Europhys. Lett.* **101**, 31003, (2013), [arXiv:1208.4669](#).
- [11] D. Aloni, Y. Nir, and E. Stamou, *JHEP* **04**, 162, (2016), [arXiv:1511.00979](#).
- [12] A. Dery, A. Efrati, Y. Hochberg, and Y. Nir, *JHEP* **1305**, 039, (2013), [arXiv:1302.3229](#).
- [13] K. Cheung, W.-Y. Keung, and P.-Y. Tseng, *Phys. Rev.* **D93**, no. 1, 015010, (2016), [arXiv:1508.01897](#).
- [14] T. Han and D. Marfatia, *Phys. Rev. Lett.* **86**, 1442–1445, (2001), [hep-ph/0008141](#).
- [15] A. Crivellin, G. D’Ambrosio, and J. Heeck, *Phys. Rev. Lett.* **114**, 151801, (2015), [arXiv:1501.00993](#).
- [16] Y. Omura, E. Senaha, and K. Tobe, *JHEP* **05**, 028, (2015), [arXiv:1502.07824](#).
- [17] I. Doršner et al., *JHEP* **06**, 108, (2015), [arXiv:1502.07784](#).
- [18] A. Crivellin, J. Heeck, and P. Stoffer, *Phys. Rev. Lett.* **116**, no. 8, 081801, (2016), [arXiv:1507.07567](#).
- [19] F. J. Botella et al., *Eur. Phys. J.* **C76**, no. 3, 161, (2016), [arXiv:1508.05101](#).
- [20] A. Arhrib et al., (2015), [arXiv:1508.06490](#).
- [21] R. Benbrik, C.-H. Chen, and T. Nomura, (2015), [arXiv:1511.08544](#).
- [22] V. Khachatryan et al., *Phys. Lett.* **B749**, 337–362, (2015), [arXiv:1502.07400](#).
- [23] G. Aad et al., *JHEP* **12**, 061, (2015), [arXiv:1509.06047](#).
- [24] CMS Collaboration, (2015), CMS-PAS-TOP-14-019.
- [25] A. Greljo, J. F. Kamenik, and J. Kopp, *JHEP* **07**, 046, (2014), [arXiv:1404.1278](#).
- [26] S. Khatibi and M. M. Najafabadi, *Phys. Rev.* **D89**, no. 5, 054011, (2014), [arXiv:1402.3073](#).
- [27] T. Plehn, G. P. Salam, and M. Spannowsky, *Phys.Rev.Lett.* **104**, 111801, (2010), [arXiv:0910.5472](#).
- [28] T. Plehn et al., *JHEP* **1010**, 078, (2010), [arXiv:1006.2833](#).
- [29] J. M. Butterworth et al., *Phys.Rev.Lett.* **100**, 242001, (2008), [arXiv:0802.2470](#).
- [30] Y. L. Dokshitzer et al., *JHEP* **9708**, 001, (1997), [hep-ph/9707323](#).
- [31] M. Cacciari, G. P. Salam, and G. Soyez, *Eur.Phys.J.* **C72**, 1896, (2012), [arXiv:1111.6097](#).
- [32] M. Buschmann, J. Kopp, J. Liu, and X.-P. Wang, (2016), [arXiv:1601.02616](#).
- [33] S. Chatrchyan et al., *JHEP* **03**, 037, (2013), [arXiv:1212.6194](#), [Erratum: *JHEP*07,041(2013)].
- [34] J. Kopp and M. Nardecchia, *JHEP* **10**, 156, (2014), [arXiv:1406.5303](#).